

Environmental aspects of oriented strand boards production. A Brazilian case study

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ABSTRACT

Use and production of industrialized wood based panels is increasing in Brazil and one of the outstanding products is the Oriented Strand Boards (OSB). At the same time, environmental concerns by companies and society about products and production systems are also growing, and the current study aims to assess the environmental impacts associated to the Brazilian OSB production in order to propose improvement alternatives focused on their profile's enhancement. Thus, a Life Cycle Assessment (LCA) study was performed according to ISO14040 and 14044 frameworks. The study covers the life cycle of OSB production from a cradle-to-gate perspective and considering real practices carried out in a representative Brazilian company. The production system has been divided in two main subsystems: Forest operations (SS1) and Panel factory (SS2). The environmental profiles have been reported considering characterization factors from the ReCiPe method, in terms of nine impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), fossil depletion (FD). According to the results, the industrial activities carried out within SS2 have been identified as the largest responsible of contributions to all impact categories under assessment. The production of pyrethroid termiticide, which is applied in the panels to improve their resistance to attack by wood decay organisms, was the largest contributor to OD, FE, HT and FET. Scenarios based on the substitution of pyrethroid termiticide were proposed and results showed that substituting the pyrethroid termiticide by different types of boron based termiticides could lead to reduce environmental impacts up to 35%. The identification of the main environmental hotspots in the OSB cradle-to-gate life cycle can assist the Brazilian industry to improve its environmental profile by adopting the proposed scenarios for SS2. Finally, further research should be focused on exploring more types of termiticides that can be applied in the OSB panel.

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1. Introduction

Brazilian wood panel market - mostly constituted by producers of Medium Density Particleboards (MDP), Medium Density Fiberboards (MDF) and Oriented Strand Boards (OSB), is considerably growing in recent years (Brazilian Association of Planted Forest Producers- ABRAF, 2013). In the period 2002–2012, the annual

production and consumption of processed wood panels had an average growth of 9% and 10%, respectively, representing the highest annual average growth of forest products in the country (ABRAF, 2013). Furthermore, Brazil is among the countries with the most advanced manufacturing processes for wood panels from reforestation trees. According to data from Brazilian industry tree – IBÁ, in 2015, the country was responsible for the production of 8 million-m³ of reconstituted wood panels, being the seventh largest worldwide producer (Ibá, 2015).

OSB market is also growing worldwide, and it is expected a growth rate of ≈28% until 2022 (Grand View Research, 2015). This

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increasing consumption by different sectors (mainly construction, furniture and packing sectors) is related with improvements into panels' properties such as strength, workability and versatility (Grand View Research, 2015). Besides that, the growing trend on plywood substitution by OSB is expected to augment demand over the forecast period 2016–2022 (Grand View Research, 2015). While plywood industry has increasingly difficulties to obtain high quality wood logs with the required dimensions to extract the blades, the OSB industry can perfectly use lower quality, unrestricted length and diameter logs as well as wood from fast-growing species (Iwakiri, 2005).

OSB are panels made of strands or wafers oriented in a controlled manner, and bonded with a waterproof synthetic resin and consolidated under heat and pressure applications. The mattress structure and particles confer to OSB excellent mechanical properties that allow the OSB to be used in many areas, especially in civil construction as well as wall coverings and roof panels (Benetto et al., 2009; Rebollar et al., 2007).

Regarding Brazil, there is only one single OSB producer with an annual production capacity of 384 m³ (LP Brasil 2015), which represents around the 8% of the total global OSB production in the world (Grand View Research, 2015). Brazilian OSB are mostly manufactured with pine wood particles obtained from dedicated forests mainly from *Pinus elliottii* and loblolly pine - *Pinus taeda* (LP Brasil 2015).

A growing concern about the environmental effects derived from the production and use of goods, as well as about how goods are disposed at the end of their life cycles, has led to the interest towards the environmental sustainability of wood-based products (Sathre and González-García, 2014). Life Cycle Assessment (LCA) is a methodology that allows assessing the environmental impacts associated to materials, products and services, as well as it supports on decision-making strategies towards sustainability (Baumann and Tillman, 2004). For that reason, LCA methodology has received special attention in recent years in order to analyze the environmental impacts derived from different production sectors such as agricultural (Meisterling et al., 2009), forest (Klein et al., 2015), bioenergy (Cherubini and Jungmeier, 2010) and food (Roy et al., 2009) sectors. Thus, LCA is used for the evaluation and choice of more environmentally friendly alternatives for a specific production system (ISO 14040, 2006a).

As regards the wood based sector, numerous studies have been carried out to determine the environmental performance of wood-based products destined for different uses such as floor coverings (Jönsson et al., 1997; Nebel et al., 2006; Petersen and Solberg, 2003), window frames (Richter and Gugerli, 1996; Salazar and Sowlati, 2008), medium density fibreboards (Rivela et al., 2007; Piekarski et al., 2017; Wilson, 2010), hardboards (González-García et al., 2009a), particleboards (Garcia and Freire, 2014; Rivela et al., 2006; Silva et al., 2013, 2014), oriented strand boards (Benetto et al., 2009; Earles et al., 2011), glue laminated timber-GLT (Puettmann and Wilson, 2004), furniture (Iritani et al., 2015; Medeiros et al., 2017; Taylor and van Langenberg, 2003), goods containers (González-García et al., 2011a), paper pulp (González-García et al., 2009b, 2011b; Silva et al., 2015), wall assemblies (Lippke and Edmonds, 2006; Werner, 2001), and packaging materials (Farreny et al., 2008). These studies have aimed to evaluate the overall environmental performance of different wood-based products, as well as to identify the processes with the highest contributions to the environmental profiles (or environmental hotspots). However, there are differences among LCA studies of wood-based products mainly concerned to the definition of the system boundaries (cradle-to-gate vs cradle-to-grave) as well as to the life cycle inventory data quality (i.e. primary or secondary datasets) and selection of environmental impact categories and

methods for the life cycle impact assessment.

It is important to highlight that there are no published LCAs of OSB produced in Brazil, although a number of studies have been developed for other regions, for instance, United States (Kline, 2005; Puettmann et al., 2012b) and Luxembourg (Benetto et al., 2009). The main differences regarding OSB produced in Brazil and in these identified regions are from the use of pyrethroid termiticide and resin types. For example, in the Brazilian OSB production process there is an application of termiticide, with the purpose of increasing its resistance to the attack of decay organisms, while for other countries there is no evidence about the application of such chemical. Besides that, MDI (methylene diphenyl diisocyanate) resin is the only binder used to produce OSB for structural applications in the Brazilian construction sector, while in the North American countries phenol-formaldehyde resins are commonly used for the adhesion of the OSB's strands of the surface layers and MDI resin is only used for adhesion of strands from the core layer.

Considering the global expected increasing market for OSB and also the need to produce more environmentally sustainable composites materials, this paper aims to quantify the potential environmental impacts related to the Brazilian OSB production in a cradle-to-gate perspective by using LCA methodology, and take decisions on the suggestions of improvement solutions to eliminate or reduce environmental hotspots.

2. Methodology

For the development of this study the ISO 14040 and 14044 (2006) standards were followed, as it will be described from sections 2.1–2.5. Thus, the four stages of an LCA study, i.e., goal and scope definition, inventory analysis, impact assessment and interpretation were organized and described as follows on the next paragraphs.

2.1. Goal and scope definition

This study aimed to analyze the cradle-to-gate production system of Brazilian OSB to detect the main environmental hotspots and to improve its environmental performance profile. The study covered the life cycle of OSB from a cradle-to-gate perspective, that is, from raw materials production up to the OSB delivery at the factory gate. The company considered for the case study is located at Ponta Grossa city, Paraná state of Brazil. The South region of Brazil is composed of three states (Rio Grande do Sul, Santa Catarina and Paraná) and it is an important industrial pole related to timber production and wood products, such as wood based panels, furniture, pulp and paper, resin extraction and sawn wood (ABRAF, 2013). Furthermore, approximately 90% of the potential Brazilian Pine production takes place in that region today (ABRAF, 2013).

2.2. Functional unit and system boundaries

Firstly, as reported in the ISO 14040 and 14044 standards (ISO 14040, 2006a; ISO 14044, 2006), the functional unit must be defined since it will provide the reference flow to which all the inputs to and outputs from the production system will be referred (ISO 14040, 2006a).

On this study, the adopted functional unit was 1 m³ of OSB produced under the classification of home type without covering, considering an average density of 600 kg/m³ and produced following the current practices performed in Brazil. A volumetric unit was used here because of prior studies on the topic, those have been also considered such functional unit for measuring all inventory and environmental life cycle impacts related to woody

panels in a cradle-to-gate perspective (González-García et al., 2009a; Silva et al., 2013, 2014).

The assessed type of board is intended to structural uses (LP Brasil 2015) and presents the following physical and mechanical requirements (EN 300): bending strength (major axis) of 22 MPa, modulus of elasticity in bending (major axis) of 3500 MPa, internal bond of 0.34 MPa and swelling in thickness after 24 h of water immersion of 15% (EN 300, 2006).

2.3. Description of the product under assessment

OSB are multi-layered boards mainly made from strands of wood together with a binder (EN 300, 2006). The strands in the external layer are aligned in parallel to the board length or width (EN 300, 2006). The strands in the internal layer can be randomly orientated, generally at right angles to the strands from the external layers (EN 300, 2006). Strand particles are manufactured with a dimension of around 25 mm of width, 90–150 mm of length and 0.5–0.75 mm of thickness (EN 300, 2006). The geometry and orientation of particles aligned in internal and external layers assist improving properties such as static bending and dimensional stability of OSB (Cloutier, 1998; Iwakiri, 2005).

The types of resins typically used in the OSB production include moisture resistant binders such as phenol formaldehyde (PF), melamine fortified with urea formaldehyde (MUF) or methylene diphenyl diisocyanate (MDI) (EPF, 2014; Spelter et al., 2006).

OSB density varies depending upon the adopted wood species and the manufacturing process itself (Mendes, 2001). However, typical densities range between 600 and 680 kg/m³. Concerning OSB commercial typical dimensions, they are 2.4 m of length, 1.2 m of width and 11.1 mm of thickness (LP Brasil 2015).

The factory under study produces 13 different types of OSB, which differ from each other in quality and application purpose. The type of OSB selected for analysis in this manuscript is known as OSB home type. In Brazil, OSB home type is manufactured with wood from coming from pine species: slash pine (*Pinus elliottii*) and loblolly pine (*Pinus taeda*), MDI resin as binder agent and paraffin wax to improve panel hygroscopic. The mattress of particles with binder and paraffin is pressed in a continuous press at 240° C of temperature and 4 MPa of pressure. The production rate of the press is about 40/45 m³/h and the average density of this type of panel is 600 kg/m³.

2.4. Description of the system under study

Fig. 1 displays the system boundaries of the OSB production system under study. The production system was divided in two main subsystems:

- Forest operations (SS1), which includes all the activities performed in the forest in order to obtain the main raw material that is, the pine roundwood.
- Panel factory (SS2), which includes all the activities carried out in the OSB panel factory from roundwood reception and debarking to the panels industrial manufacturing and finishing process.

Regarding SS1, all the main activities performed in the forest production were analyzed. The average lifespan to produce pine wood for OSB production is 12 years. As reported in Fig. 1, forest activities have been classified in four main stages: Soil preparation, Seedlings plantation, Forest management and Forest harvesting.

Soil preparation (0 year): this stage involves soil treatment related operations, such as soil fertilization with urea, ammonium sulphate, potassium chloride and superphosphate as well as the treatment with herbicide (glyphosate) and insecticide

(sulfluramide based ant bait) as reported by Silva et al. (2013). Besides that, it involves operations such as subsoiling, lowering strains and waste scattering, and road building and maintenance related operations during the lifespan period (0–12).

Seedlings plantation (0 year): this stage consists on planting pine seedlings at a rate of 1750 seedlings per hectare in the stand followed by irrigation. Seedling production at a nursery process has been excluded from the system boundaries due to lack of primary available data.

Forest management (1st –12th year): after planting, forest management activities are carried out, such as mineral fertilization (application of urea, ammonium sulphate, potassium chloride and superphosphate), chemical weeding (application of glyphosate based herbicide) and pest control (application of sulfluramide based ant bait).

Forest harvesting (12th year): wood is harvested by means of a harvester machine and transported by trucks to the OSB factory.

In relation to SS2, the different processes carried out within the factory have been divided in eight main activities in Fig. 1: roundwood debarking, chipping, particles drying, particles screening, blending, mat formation, hot pressing, finishing, hot generation and composting.

Logs debarking: pine roundwood are received in the factory and storage in the courtyard before bark extraction. The logs are then debarked before their transformation into strands. Bark is removed because it may cause a negative effect into the physical-mechanical properties of manufactured OSB.

Chipping: debarked roundwood are transformed into strand particles by means of chippers.

Particles drying: in this stage, particles are dried through contact with hot gas until the appropriate moisture content is reached, that is usually between 4% and 6%. The hot gas flow derives from the bark and woody residual biomass (e.g. sawdust from screening process and cutting waste) combustion in a heat generation unit.

Particles screening: this process screens out fine wood materials from dried strands that are considered too small for OSB mat formation. The rejected particles are burned in the heat generation unit in order to produce the heat required in the strands drying step, as well as to heat the oil used in the hot pressing machine.

Blending: liquid resin with small amounts of wax and pyrethroid are forced through nozzles and sprayed onto the strands. As previously reported, MDI resin is used in OSB home type production, because it confers to the panel higher quality. The application of paraffin wax and pyrethroid termiticide aims to improve hygroscopicity of the finished product and the panel's resistance to the attack of organisms decay, respectively.

Mat forming: the glued particles are directed to the forming unit where they are arranged in three layers. The particles of the external layers are arranged perpendicular to the outer layer.

Hot pressing: the formed particle mattress is sent to the pressing machine, where the OSB panel consolidation occurs through the application of pressure and temperature during a specific time to promote the curing of the resin.

Finishing: the cooled board is directed to a sander unit, where the thickness is standardized and surface irregularities are removed. After surface treatment, the OSB cutting step takes place according to customer requirements regarding board length and width dimensions. The cutting wastes are sent to the hot heat generation process for heat production.

Heat generation: bark and biomass waste (rejected particles from the screening and cutting processes) are burnt to produce the heat requirements for the particles drying process and to warm the thermal oil required in the hot pressing process.

Composting: finally, residues such as ash from the heat generation unit are sent to composting.

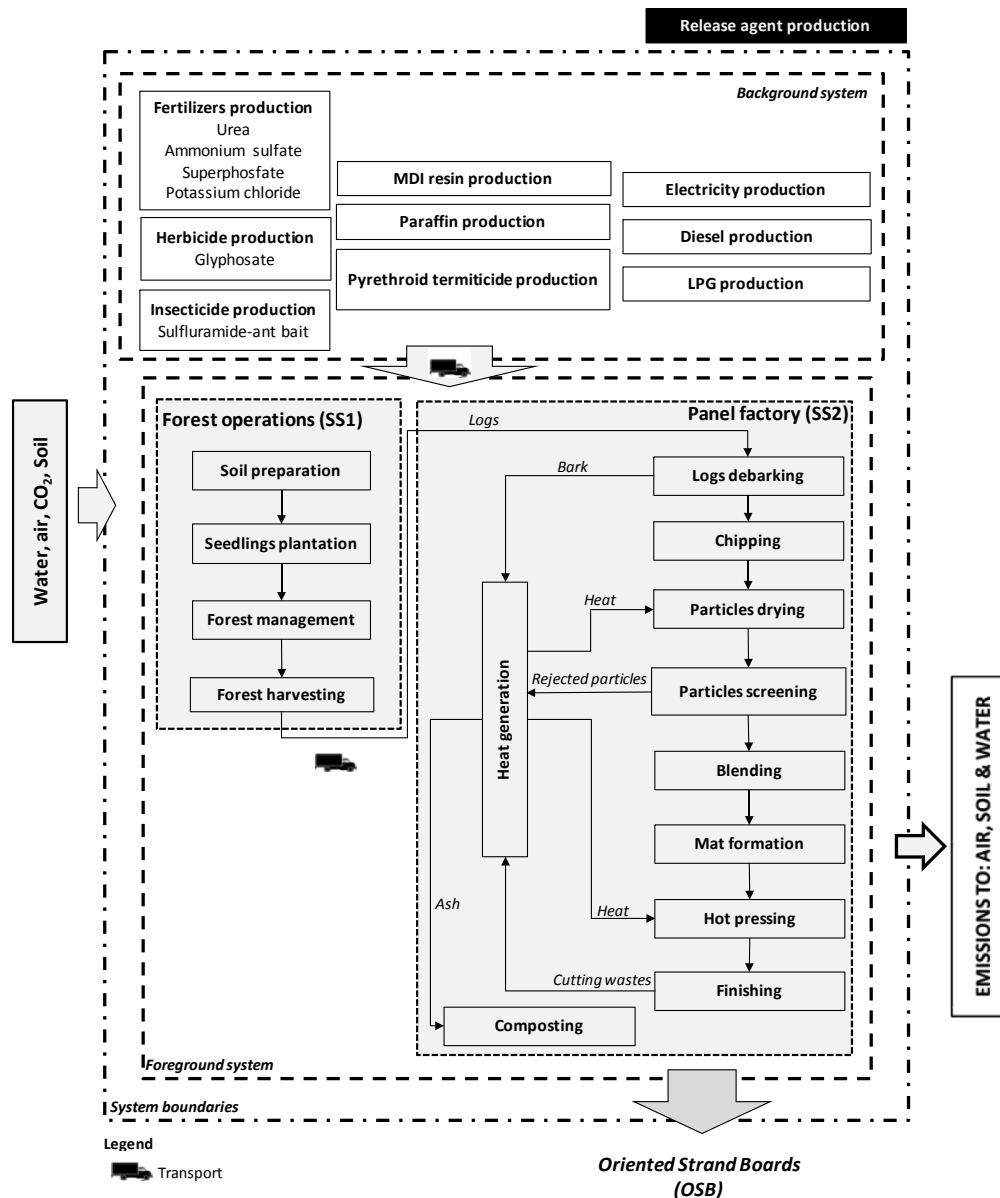


Fig. 1. System boundaries of the OSB life-cycle production system under study (cradle-to-gate perspective). Black boxes correspond to processes excluded from the system boundaries.

As it can be seen in Fig. 1, a number of ancillary processes were included within the system boundaries as background processes. Background processes includes: i) the production of energy inputs such as electricity for the Brazilian national grid and fossil fuels (diesel and liquefied petroleum gas - LPG required for internal transports in the panel factory), ii) the production of chemicals required in SS1 related activities such as mineral fertilizers (urea, ammonium sulfate, potassium chloride and superphosphate) and herbicides (glyphosate), as well as chemicals used in SS2 such as MDI resin, paraffin and pyrethroid termiticide. In addition, it was included also the transportation activities related with the inputs distribution up to the both forest stand and OSB factory from the corresponding production/retailer sites.

2.5. Life cycle inventory and data quality

The data quality for the Life Cycle Inventory (LCI) is an important issue to be addressed in a LCA study. According to ISO 14040 and

14044 (2006) standards, the data quality should address some requirements, among them the description of data sources.

The real and characteristic primary data should be considered in order to obtain more accurate and representative environmental results in a LCA. In this study, only primary data were managed for the foreground system from Fig. 1.

The inventory data corresponding to the panel factory (SS2) consisted on average production data covering 2015–2016, which were obtained by on-site measurements. Average transport distances corresponding to the inputs delivery up to the panel factory gate are presented in Table 1. It was assumed that all the transport activities were performed by trucks with a payload higher than 32 ton - EURO 5 category (Spielmann et al., 2007), except the MDI resin, which is imported from Germany and transported by ship up to Brazil.

About the background processes, inventory data was collected from literature. Therefore, secondary data related with the production of chemicals required in SS2 (MDI resin, paraffin and

Table 1

Transport distances. Acronyms: SS1 – Forest operations; SS2- Pulp factory.

Subsystem	Inputs	Distance (km)
SS2	Wood	150
SS2	MDI resin ^a	9000
SS2	Paraffin	100
SS2	Pyrethroid termiticide	100
SS1	Urea	2117
SS1	Ammonium sulfate	2389
SS1	P-based fertilizer	2173
SS1	K-based fertilizer	2634
SS1	Glyphosate	2403
SS1	Sulfuramide	566

^a Imported from Germany and transported by ship.

pyrethroid termiticide) were taken from Althaus et al. (2007). Regarding the production of the Brazilian electricity and fossil fuels (diesel and LPG), inventory datasets were obtained from Dones et al. (2007).

OSB manufacture requires electricity and heat. Electricity requirements are totally satisfied by the Brazilian national grid and it is consumed by all machines used in the industrial processes of OSB. In relation to heat requirements for drying process and hot pressing unit, heat is produced on-site in a heat generation unit where wasted biomass (bark from debarking process, fine particles from screening process and other residues) is combusted.

Fossil fuels such as diesel are used by tractors for roundwood transportation from the storage place until the debarking machine, and LPG is consumed by forklift vehicles for internal activates transportation of OSB in the factory.

As regards to outputs to environment derived from SS2 related activities, primary data was considered and when emission data was not available, they were estimated based on literature data sources. Thus, emissions from the combustion of fossil fuels such as diesel and LPG used in internal transport were taken from Spielmann et al. (2007) and IDEMAT 2001 database (Idemat, 2001), respectively. Regarding bark and biomass waste combustion, emissions were taken from Doka (2009). Concerning the drying and hot pressing processes, volatile organic compounds (VOC) are emitted into the atmosphere, and data concerning these emissions were taken from Kline (2010).

Table 2 shows the summarized global inventory for the industrial production of 1 m³ of OSB home type.

Water requirements for the OSB production at the panel factory were satisfied from a close river.

The production and maintenance of capital goods required in SS2 were excluded from the analyses. In line with this, several LCA studies have reported that environmental loads derived from the production of capital goods are insignificant (Rivela et al., 2006, 2007) in relation to the burdens derived from the whole investigated product system for LCA of wood-based panels.

Concerning Forest operation subsystem (SS1), the data were obtained by on-site measurements in forest stands in collaboration with forest workers from the studied company. The forest stands under assessment are located 150 km far from the OSB plant. The average productivity is around 40 m³ of roundwood per ha and year (481.2 m³ · ha⁻¹ after 12 years). All inputs to and outputs from SS1 have been calculated and allocated to the functional unit considered on this study, i.e., 1 m³ of OSB home type. Thus, 2.42 tonnes of roundwood (see Table 2) are required, and this is equivalent to 1.24 · 10⁻² ha. Table 3 shows a summary of LCI data for SS1.

Inventory data corresponding to the ancillary processes in SS1 was collected from literature. Data related with the production of mineral fertilizers (urea, ammonium sulfate, superphosphate and potassium chloride), as well as herbicide supply (glyphosate) were

Table 2Global inventory data (*gate-to-gate* perspective) per functional unit (1 m³ of OSB Home type at factory gate) corresponding to the SS2 (Panel factory).

	Quantity	Unit
INPUTS FROM TECHNOSPHERE		
Materials		
Pine logs (from SS1)	2419	kg
MDI resin	14.7	kg
Paraffin	7	kg
Pyrethroid termiticide	0.96	kg
Release agent	0.70	kg
Fossil fuels		
Liquefied Petroleum Gas (LPG)	0.18	kg
Diesel	0.98	kg
Energy		
Waste Biomass ^a	6131	MJ
Electricity	497	MJ
Transport		
Truck	38	t · km
Ship	14	t · km
INPUTS FROM ENVIRONMENT		
Water	0.29	kg
OUTPUTS TO TECHNOSPHERE		
Product		
Oriented Strand Boards (OSB)	1	m ³
Waste to treatment		
Ash ^b	38	kg
OUTPUTS TO ENVIRONMENT		
Emissions into air		
<i>from Heat generation step</i>		
Particles	3.8	kg
CO	4.6	kg
CO ₂	1500	kg
NO _x	1.7	kg
SO ₂	0.19	kg
CH ₄	0.16	kg
Steam	65	g
<i>from Drying and Hot pressing steps</i>		
VOC	4.2	kg
MDI	32	g
<i>from internal transportation</i>		
CO	5.8	g
CO ₂	3056	g
NO _x	38	g
VOC	0.98	g
SO ₂	1.0	g
NM VOC	342	g
Particles (<2.5 μm)	4.8	g

^a From logs debarking, screening process and cutting waste.^b From Heat generation unit to Composting unit.

taken from Althaus et al. (2007).

Direct emissions into air and water derived from herbicide applications were estimated by means of the method reported by Jansma and Linders (1995). Emissions into air and water resulting from the application of urea and ammonium sulfate were estimated based on emission factors reported by the Klein et al. (2006). Regarding phosphate emission into water derived from superphosphate application, it was calculated in accordance with Rossier (1998). With regard to emissions from potassium chloride application, it was assumed that there were no emissions into the air, water or soil in accordance with Silva et al. (2013).

Combustion emissions derived from diesel use in the forest machines, as well as from transport activities related with inputs supply up to the forest site, were taken from Nemecek and Kägi (2007) and Spielmann et al. (2007), respectively.

3. Life cycle impact assessment

The assessment of the environmental impacts associated with the OSB production system was conducted considering

Table 3

Summarized inventory data corresponding to pine roundwood production at forest stand in order to produce 1 m³ of OSB Home type.

	Quantity	Unit
INPUTS FROM TECHNOSPHERE		
<i>Materials</i>		
Seedlings	22	unit
<i>Herbicide</i>		
Glyphosate	240	g
<i>Insecticide</i>		
Sulfluramide based ant bait	480	g
<i>Fertilizers</i>		
Urea	126	g
Ammonium sulfate	58	g
Superphosphate	1365	g
Potassium chloride	458	g
<i>Fossil fuels</i>		
Diesel	350	g
<i>Transport</i>		
Truck	420	t · km
OUTPUTS TO TECHNOSPHERE		
<i>Product</i>		
Pine roundwood	400	kg
OUTPUTS TO ENVIRONMENT		
<i>Emissions into air</i>		
<i>from diesel combustion</i>		
NM VOC	60	g
NO _x	507	g
CO	153	g
CO ₂	29	kg
SO ₂	24	g
CH ₄	21	g
Benzene	26	g
Particles	80	g
Cadmium	63	g
Chromium	63	g
Copper	63	g
N ₂ O	21	g
Nickel	63	g
Zinc	63	g
Benzo(a)pyrene	26	g
PAH ^a	38	g
Heat	428	kg
Ammonia	19	g
Selenium	63	g
<i>from fertilizers application</i>		
Urea	100	g
<i>from glyphosate herbicide application</i>		
Glyphosate particles	21	g
<i>Emissions into soil</i>		
<i>from glyphosate herbicide application</i>		
Glyphosate particles	179	g
<i>Emissions into water</i>		
<i>from glyphosate herbicide application</i>		
Glyphosate particles	21	g
<i>from fertilizers application</i>		
Nitrate leaching	40	g
Phosphate	1,1	g

^a polycyclic aromatic hydrocarbons.

characterization factors reported by ReCiPe Midpoint method (Goedkoop et al., 2009). Ten impact categories were selected for assessment taking into account the main categories analyzed in LCA studies those have focused not only on woody panels but also in other woody systems (González-García et al., 2009a, 2011a; Silva et al., 2013, 2014; 2015): climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET) and fossil depletion (FD). The software SimaPro v. 8.02 (PRé Consultants, 2017) was managed to implement the LCI datasets.

Table 4

Potential environmental impacts per 1 m³ of OSB Home type.

Impact category	Unit	Total	SS1	SS2
CC	kg CO ₂ eq	127	12	115
OD	kg CFC-11 eq	8.3 · 10 ⁻⁶	1.9 · 10 ⁻⁶	6.4 · 10 ⁻⁶
TA	kg SO ₂ eq	1.82	0.09	0.92
FE	kg P eq	0.01	4.1 · 10 ⁻³	5.9 · 10 ⁻³
ME	kg N eq	0.07	1.7 · 10 ⁻⁴	0.07
HT	kg 1,4-DCB eq	10	3.28	6.72
POF	kg NMVOC eq	1.86	0.14	1.72
TET	kg 1,4-DCB eq	0.03	0.01	0.02
FET	kg 1,4-DCB eq	0.23	0.08	0.15
FD	kg oil eq	50	4.12	45

3.1. Overall LCA environmental profiles

The life cycle impact assessment (LCIA) step establishes links between the LCI data with potential environmental impacts (Puettmann et al., 2012b). Table 4 shows the environmental burdens obtained per impact category for the Brazilian OSB production system considering 1 m³ of OSB home type.

As it can be seen in Table 4, the highest contributions are attributed to SS2 (panel factory), with ratios ranging more than 90% for all the impact categories.

Fig. 2 displays the relative contributions to each impact category from the main contributing factors involved in the Brazilian OSB cradle-to-gate life cycle.

A detailed discussion of the impacts on each category is given below.

Climate change potential (CC): According to the results, MDI resin production was responsible for 38% of the total CO₂ eq emissions produced throughout the product system, mainly due to the use of crude oil in its manufacturing (it is a petroleum based resin), which contributes to approximately 78% of CO₂ emissions derived from this process. The second most contributor was Electricity production, responsible for 20% of the total equivalent CO₂ emissions, mainly due to the use of non-renewable sources such as coal and oil from the Brazilian electric mix.

Ozone depletion potential (OD): According to Fig. 2, the production of chemicals such as paraffin and pyrethroid termiticide

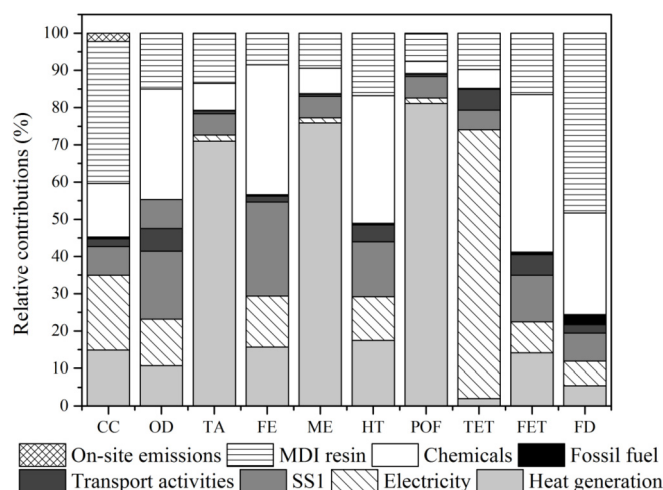


Fig. 2. Relative contributions (in %) to each impact category per outstanding contributions factors involved in the Brazilian OSB Home type production life cycle. Acronyms: CC – Climate Change; OD – Ozone Depletion; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human Toxicity; POF – Photochemical Oxidant Formation; TET – Terrestrial Ecotoxicity; FET – Freshwater Ecotoxicity; FD – Fossil Depletion.

was the largest contributor ($\approx 30\%$) to this impact category, mainly due to the high amount of methane (CH_4) emitted into atmosphere during the production of carbon tetrachloride (CCl_4), one of the main raw materials required in the production chain of termiticide. The second largest contributor was the roundwood (SS1) with a contributing ratio of 19%, mostly due to the high amounts of diesel required by the harvester used in the forest harvesting stage. The third largest contributor was the MDI resin (15% of the total CFC_{-11} eq emitted), as a result of using crude oil as raw material for the MDI resin production.

Terrestrial acidification potential (TA): Emissions produced during the heat generation were responsible for 71% of total SO_2 eq emitted to the atmosphere. Combustion gases from the heat generation unit, such as NH_3 and SO_2 due to the bark and woody residual biomass (e.g. sawdust and cutting waste) are remarkable contributing substances to TA. The MDI resin production was responsible for $\approx 12\%$ of the total acidifying emissions, mostly related to SO_2 releases produced during the resin manufacturing process.

Freshwater eutrophication potential (FE): The production of chemicals such as paraffin and pyrethroid termiticide was responsible for the majority of the impacts ($\approx 35\%$ of total P eq emitted), and pyrethroid termiticide was the main responsible one. In the termiticide production process, the main energy requirements come from a heat generation unit based on burning heavy fuel oil. SS1 was the second largest contributor for this impact category ($\approx 25\%$), because contributing substances to FE are mainly related with the superphosphate production, as a result of the P-fertilizer used in the soil preparation and forest management stages.

Marine eutrophication potential (ME): Approximately 75% of the impacts contributing to this category are related with the emissions produced during the heat generation process due to the nitrous oxides (NO_x) releases into the atmosphere. MDI resin production was the second largest contributor to this category ($\approx 9\%$ of total N eq emitted), mostly due to its fossil origin.

Human toxicity potential (HT): Production of chemicals that is, paraffin and pyrethroid termiticide, was responsible for 34% of total equivalent 1,4-dichlorobenzene (1,4-DCB eq) emissions. In fact, production of pyrethroid termiticide contributes to 86% of that ratio, due to air emissions of metals Mn and As. Production of MDI resin was 17% of the total contributions to HT, mainly due to the CH_4 emission derived from its manufacturing processes.

Photochemical oxidant formation potential (POF): Emissions produced in the heat generation unit are responsible for 81% of the POF impacts. Gases such as NO_x , carbon monoxide (CO) and CH_4 from combustion of bark and woody residual biomass are emitted into atmosphere and they contribute to the POF impacts. In a second place, MDI resin production accounts for approximately 7% of the POF impacts, as a result of NMVOC emissions (non-methane volatile organic compounds), mostly because of emissions of NO_x derived from its petroleum-based origin.

Terrestrial ecotoxicity potential (TET): Electricity production represents more than 72% of the total TET impacts. This high ratio was related with the Brazilian electric mix, which partly depends on renewable sources from thermoelectric plants – mostly sugarcane bagasse. The agricultural activities involved in the production of sugarcane, specifically those related with soil preparation were considered as the main responsible for TET impacts. MDI resin production was the second most important contributor ($\approx 10\%$), due to the direct emissions of chlorohydrin from its manufacturing process.

Freshwater ecotoxicity potential (FET): Production of chemicals involves approximately 42% of the FET impacts, especially due to the pyrethroid termiticide (30% of total contributing substances).

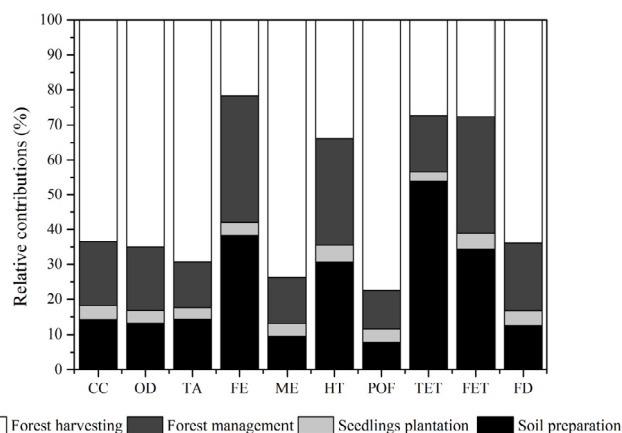


Fig. 3. Relative contributions to each impact category (in %) per forest stages considered in the Brazilian Pine roundwood production chain (SS1) under study. Acronyms: CC – Climate Change; OD – Ozone Depletion; TA – Terrestrial Acidification; FE – Freshwater Eutrophication; ME – Marine Eutrophication; HT – Human Toxicity; POF – Photochemical Oxidant Formation; TET – Terrestrial Ecotoxicity; FET – Freshwater Ecotoxicity; FD – Fossil Depletion.

Emissions such as Cu and Mg metals into water were the main hotspots and they are derived from the manufacturing process of the termiticide. The production of MDI resin was responsible for 16% of the total FET impacts, since metals such as Cu and Mg to water were also associated with the resin manufacturing process.

Fossil depletion potential (FD): Contributions from MDI resin production were near 48% of the total FD impacts, followed by far by the production of chemicals (paraffin and pyrethroid termiticide) with 27%. These chemicals are derived from petroleum so, extraction of crude oil is a higher contributor to FD.

Fig. 3 displays a detailed distribution of the environmental impacts from the production of the main OSB panel's raw material, i.e., pine roundwood (SS1). Harvesting stage, which consists of three operations: harvesting, forwarding, and loading of roundwood, is the environmental hotspot for all the categories under analysis except for FE, HT and FET. The harvester and the forwarder are large machines which present an outstanding diesel consumption rate ($\approx 940 \text{ L ha}^{-1}$) and operating hours (40 h) and thus, they generate high amounts of combustion air emissions such as SO_2 , CO_2 , CO and NO_x .

4. Discussion

As it can be seen in Fig. 2, four factors can significantly influence on the environmental impacts under study: production of MDI resin and remaining chemicals used in the panel factory (paraffin and termiticide), on-site emissions throughout the manufacturing system, and finally the supply of electricity. The identification of these contributing factors agree with other studies on which different woody panels were analyzed (González-García et al., 2009a,b; Rivel et al., 2006; Silva et al., 2013).

Concerning the chemicals used in the OSB production, the pyrethroid is an organic compound that constitutes the termiticide, and it is applied on the panels to protect them against the attack of decay organisms such as fungi and termites. The production of pyrethroid termiticide mainly contributes to impact categories such as OD, FE, HT and FET. Comparing results with other LCA studies that focused on OSB production, such as United States (Kline, 2010) and Canada (Puettmann et al., 2012a), only in the Brazilian manufacturing system exists the application of termiticide. However, other existing studies (Sean et al., 1999; Murphy et al., 1995; Xu et al., 2013) have considered the application of

boron based products in the production of OSB in order to improve the panels resistance to attack of fungi and termites. Thus, this paper proposes two alternative scenarios considering the substitution of the pyrethroid termiticide by specific amounts of boron based termiticides to determine its influence on the environmental profile of the Brazilian OSB and to demonstrate (or not) the environmental benefits of using boron instead of pyrethroid.

The Brazilian OSB plant generates a high amount of energy from the biomass combustion unit. This process (heat generation) shows a high contribution to impact on categories such as ME, PO and TA. On this sense, heat generation process can be also considered as an environmental hotspot, and this is in line with other LCA studies on the topic (González-García et al., 2009a,b; Kline, 2010). Silva et al. (2013) have analyzed the production of Brazilian MDP from a LCA perspective and considering four alternatives of fuel to generate the plant heat requirements, such as heavy fuel oil, diesel, wood waste, and a mix of diesel with wood waste supply. Results from that study showed that the use of only wood waste as fuel presents the lowest impacts for acidification, eutrophication, abiotic depletion, photochemical oxidation and global warming. Based on such literature background, scenarios focused on the use of alternative fuels in the OSB heat generation have been excluded from the scenario analysis.

About the production of MDI resin, the use of crude oil on its manufacturing process considerably contributes to impacts such as CC and FD. An outstanding improvement could be achieved if the MDI resin would be replaced by a bio-resin such as tannin based and lignin based adhesives (Dewar, 2007) or bio-based phenolic materials in combination with phenol-oxidizing enzymes (González-García et al., 2011b). Nonetheless, it is firstly mandatory the assessment of the bio-resins effect on the physical and mechanical properties of the manufactured panel. The substitution of MDI resin by bio-resins could negatively change the technical properties of the panel, which could not be desirable.

4.1. Substitution of pyrethroid by boron compounds

Based on three studies found in literature, Sean et al. (1999), Murphy et al. (1995) and Xu et al. (2013), which have used boron based termiticides to improve the OSB resistance to attack of wood decay organisms, two alternative scenarios were proposed. These scenarios are based on the use of calcium borate (Scenario 2) and sodium borate (Scenario 3), as two alternatives to the use of pyrethroid termiticide (Scenario 1).

Scenario 1 was considered as the baseline and corresponds to the current OSB Brazilian production system where 0.96 kg of pyrethroid termiticide is used per functional unit (1 m³ of OSB), as described on the inventory from Table 2. Scenario 2 and Scenario 3 assume that the amount of calcium borate and sodium borate are, respectively, applied following the recommendations provided by Murphy et al. (1995) and Xu et al. (2013). According to these authors, for the production of 1 m³ of OSB home type is necessary to apply 10.3 kg of calcium borate (Scenario 2) and 0.5 kg of sodium borate (Scenario 3).

Fig. 4 shows a comparative LCA results for the three scenarios under analysis. The impact categories analyzed were only OD, HT, FE and FET since these are the impact categories mostly affected by the production of pyrethroid termiticide, as previously indicated.

As it can be seen in Fig. 4, there are no significant differences in the impacts between the Scenarios 2 and 3, because differences were no higher than 2%. However, when Scenarios 2 and 3 are compared with Scenario 1, their environmental profiles showed a great potential reduction with avoided impacts ranging from 29 to 43% depending on the impact category.

The major environmental benefits are associated with FE impacts. A reduction of 43% could be achieved by means of the use of

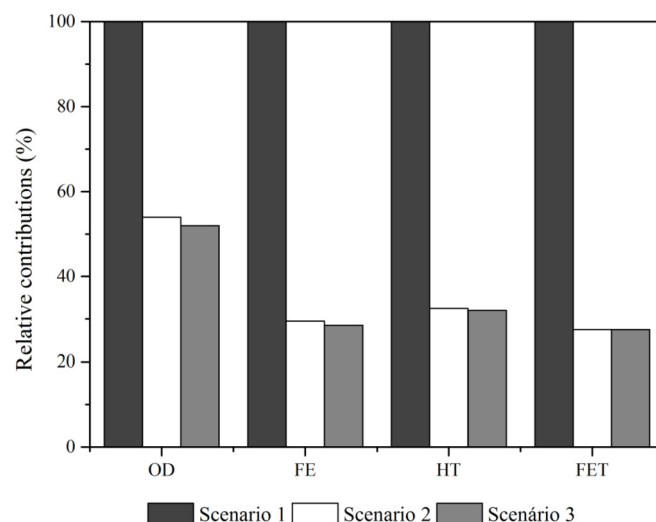


Fig. 4. Comparative environmental impact assessment of the three scenarios profiles between the three alternative scenarios proposed for assessment based on the use of different termiticides: Scenario 1 – Pyrethroid termiticide; Scenario 2 – Calcium borate termiticide; Scenario 3 – Sodium borate termiticide. Acronyms: OD –Ozone Depletion, FE- Freshwater Eutrophication, HU- Human Toxicity.

sodium borate termiticide (Scenario 3), and 41% if calcium borate termiticide (Scenario 2) is considered. The avoided impacts are mainly related with:

- the energy requirements associated to the production of each type of termiticide. In the pyrethroid termiticide production, substantial amounts of heat are required, and they are produced on-site from burning fossil fuels. However, in the production of both calcium borate and sodium borate based termiticides, electricity is needed instead of fossil fuels;
- differences on the termiticide consumption ratios. Around 1 kg of pyrethroid termiticide is required in Scenario 1. However, 10.3 kg and 0.5 kg of calcium borate and sodium borate based termiticides are needed for Scenarios 2 and 3, respectively.

The environmental improvement in terms of HT is related with energy consumption and the best environmental profile was for the use of boron based termiticide. The best environmental profile is indirectly associated to the energy requirements for production of the termiticide, as previously discussed also on i). With regard to OD, the best environmental profiles are also associated to Scenario 2 and Scenario 3, with approximately 30% less impacts in relation to Scenario 1. For the production of pyrethroid termiticide, CCl₄ component is used as raw material, and this is the primarily responsible for the high levels of impacts on HT and OD.

Finally, the displacement of pyrethroid termiticide by boron based termiticides should be considered to produce also OSB in Brazil, in order to improve the environmental profile of the manufactured panels in a cradle-to-gate life cycle approach. However, further analysis should be required specifically in terms resistance of the panel to attack by wood decay organisms when calcium borate and sodium borate are used instead of pyrethroid termiticide. Besides that, it is also necessary to perform a LCA to evaluate a cradle-to-grave perspective of the OSB to compare results of using all these types of termiticides. The environmental impacts of the use and post-use phases of the OSB could be affected by the different possible termiticides applications, and a whole LCA study would help to address this issue.

5. Conclusions

This study performed a cradle-to-gate LCA of OSB production in Brazil, considering two main subsystems - Forest operations (SS1) and Panel factory (SS2). The environmental hotspots over the life cycle of the OSB were identified and potential improvement alternatives were suggested and analyzed. SS2 was identified as the most responsible for the overall impacts with a contributing ratio of 90% regardless the impact category under study. The main environmental hotspots were identified as: i) the production of the petroleum based chemicals used in the OSB formulation (mainly the pyrethroid termiticide and the MDI resin), and ii) the diverse emissions (to air and water) derived from activities in the OSB manufacturing (mostly the ones produced in the heat generation unit where biomass waste is burned). About SS1, environmental results showed that FE, OD, and FD are the impact categories mostly affected by forest activities due to the considerable amounts of diesel required in the forest machines, specifically in the harvesting stage.

The LCA results showed on this paper are in line with other prior studies on the topic, and two alternative scenarios were proposed for the substitution of the pyrethroid termiticide by boron based termiticides – Scenario 2: calcium borate termiticide, and Scenario 3: sodium borate termiticide. According to the environmental burdens of each scenario compared with the baseline one, remarkable improvements could be achieved in terms avoided impacts to OD, FE, HT and FET, with reduction ratios ranging from 30% to 43%. However, further research should be addressed in terms of the termiticide substitution by boron compounds in relation to the effects on the OSB panels resistance to attack by wood decay organisms and in terms of the physical and mechanical properties of the panels too. In addition, the environmental impacts of the use and post-use phases of the OSB should be investigated to cover a cradle-to-grave life cycle of OSB in Brazil, and also to analyze the effect of consuming different termiticides (Scenarios 1, 2 and 3) under the LCA results.

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